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Prof. Albert P. Pisano (PI), Prof. Carlos Fernandez-Pello, Christopher McCoy, John Reville, Jesse Limtiaco

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14. ABSTRACT

The ultimate goal of the fuel flexibility project is to deliver on-demand, reliable, small-scale portable power using internal combustion engines that run on a variety of fuels. This will require advanced control of the combustion event, dramatic improvements to the engine sealing technology, and development of integrated sensors and feedback for optimal performance. To achieve this goal, a specialized engine test platform needs to be designed and built to accurately measure power output, torque, and efficiency. Upon collecting these data, a baseline for engine

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Report Title

FINAL REPORT: Fuel Flexible Rotary Engine for Portable Power Applications

ABSTRACT

The ultimate goal of the fuel flexibility project is to deliver on-demand, reliable, small-scale portable power using internal combustion engines that run on a variety of fuels. This will require advanced control of the combustion event, dramatic improvements to the engine sealing technology, and development of integrated sensors and feedback for optimal performance. To achieve this goal, a specialized engine test platform needs to be designed and built to accurately measure power output, torque, and efficiency. Upon collecting these data, a baseline for engine performance on its standard fuel can be established and will enable performance comparisons using other fuels, new design features (i.e. seals), and control systems. The second phase of design will begin to optimize the engine performance in real time using sensors and actuators that monitor and control engine performance parameters. Using this sensor data, feedback and control algorithms can be designed, debugged, and implemented to run the engine at maximum power or efficiency.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

1. Poster Presentation: McCoy, C., Réville, J. “Fuel flexible engine design for optimal combustion.” Poster Session. Massachusetts Institute of Technology Energy Conference. March 2009.

2. Poster Presentation: McCoy, C. “Fuel flexible engine design for optimal combustion.” presented at BSAC Spring 2008 IAB Meeting, Mar. 2009.

3. Poster Presentation: McCoy, C. “Fuel flexible engine design for optimal combustion.” presented at BSAC Fall 2008 IAB Meeting, Sept. 2008.

4. Poster Presentation: McCoy, C. “Fuel flexible engine design for optimal combustion.” presented at BSAC Spring 2009 IAB Meeting, Mar. 2008.

5. Poster Presentation: McCoy, C. “Fuel flexible engine design for optimal combustion.” presented at BSAC Fall 2009 IAB Meeting, Sept. 2007.

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Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Christopher McCoy	0.48
John Reville	0.00
Jesse Limtiaco	0.48
FTE Equivalent:	**0.96**
Total Number:	**3**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Albert P. Pisano	0.00	Yes
Carlos Fernandez-Pello	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	0.00

Names of Personnel receiving masters degrees

NAME
John Reville
Jesse Limtiaco

Total Number: **2**

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Fuel-flexible Engines for Portable-Power Applications

Chris D. McCoy, John Réville, Jesse Limtiaco, Matt Hopcroft and Albert P. Pisano

***Abstract*— the ultimate goal of the fuel flexibility project is to deliver on-demand, reliable, small-scale portable power using internal combustion engines that run on a variety of fuels. This will require advanced control of the combustion event, dramatic improvements to the engine sealing technology, and development of integrated sensors and feedback for optimal performance. To achieve this goal, a specialized engine test platform needs to be designed and built to accurately measure power output, torque, and efficiency. Upon collecting these data, a baseline for engine performance on its standard fuel can be established and will enable performance comparisons using other fuels, new design features (i.e. seals), and control systems.**

The second phase of this research will begin to optimize the engine performance in real time using sensors and actuators that monitor and control engine performance parameters. Using these sensor data, active feedback and control algorithms can be designed, debugged, and implemented to run the engine at maximum power or efficiency in multi-fuel operation.

Baseline testing demonstrated that the engine could produce brake mean effective pressures of 240kPa at 12000RPM, 89kPa at 8300RPM and 149kPa at 12000RPM for Methanol, 87 Octane, and military grade, JP8, respectively.

Repeated testing procedures elucidated the need for better measurement and control of the glow plug intensity, the external engine temperature, and throttle measurement. Other complications with the data acquisition software and measurement hardware (LabVIEW and Ohaus fuel scale) are still problems in the process of being resolved.

Future work would include additional control via embedded systems and more robust control and measurement of key parameters (throttle and air-to-fuel ratio). The three-tiered research approach consists of the following: a pre-combustion phase, in-situ combustion phase, and a post-combustion phase.

***Index Terms*—fuel-flexibility, power generation, Wankel rotary engine, renewable fuels**

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Chris D. McCoy is with University of California at Berkeley pursuing his Ph.D. in mechanical engineering and is a member of the Berkeley Micromechanical Analysis and Design (BMAD) Lab. He is the corresponding author (510.643.1099; fax: 510.643.6637; e-mail: mccoy@eecs.berkeley.edu).

John Réville, has graduated from the University of California at Berkeley with his Masters degree. He is now an instructor at UC Extensions.

Jesse Limtiaco graduated from the University of California at Berkeley, with his Masters degree in mechanical engineering.

Albert P. Pisano is the acting Dean of Engineering at the University of California at Berkeley and advisor of the Berkeley Micromechanical Analysis and Design Lab.

I. Introduction

"Up to 70 percent of the tonnage delivered to deployed forces is fuel. Fuel delivery convoys to deployed forces add costs to the logistical chain and create targets for IEDs, the single greatest source of casualties in Iraq." The Defense Industry Daily article goes on to say that much of this fuel is not just for vehicles, but for generators. Having flexibility to scavenge fuel and to perform smart combustion could potentially reduce the amount of fuel needing transportation [4].

A. Relevance to the Army

The two main capabilities of the fuel flexible rotary engine are battery recharge and as a power source for other auxiliary military electronic equipment. Both have importance consequences for military operations. Battery consumption for powering military equipment is a significant cost and logistical burden for modern forces. A fuel-flexible recharging station could use locally available fuel supplies and conventional (automobile) fuel supply chains, reducing the reliance on costly and vulnerable JP-8 supplies. Auxiliary power for military equipment has the potential to significantly reduce the Army's dependence on primary cell batteries and larger vehicle power from its engine. The ability to turn off the vehicle main engine when the vehicle is at rest and continue to operate communication, sensing, environment, and other systems increases vehicle survivability by reducing exhaust signature. Operational range is increased by reducing fuel consumption and transferring some power consumption to locally-sourced fuels.

B. Properties of Combusted Fuels

The following chart describes the advantages and disadvantages of different fuels that are currently available for market consumption.

While petroleum-based fuels are being tested in this research, the researchers are particularly interested in the engine's ability to combust bio and renewable fuels.

Fuel	Advantages	Disadvantages
Gasoline	+Inexpensive, volatile	–Limited supply, volatile, toxic (benzene = carcenogenic)
Diesel	+Sometimes cheaper than gasoline	–High soot formation, sulfer content, viscosity =f(T)
BioDiesel	+Acts as a cleaning agent, high cetane number	–Poor economic feasibility (oil>$80/barrel), 10% less energy dense than reg. diesel
Bio/Butanol	+Used in autos without modification, high octane rating (100+), 50% more energy dense than ethanol	–High flashpoint (95 deg. F), toxic, foul fermentation odor, $0.57-0.58/lb,
Kerosene	+Used as an additive in diesel fuel to prevent gelling in T_C heavy use in military	–Fossil fuel based
Methanol	+Used as an additive to increase octane rating	–Fossil fuel based, toxic
Bio/Ethanol	+Inexpensive, renewable	–Toxic, low energy density
Synthetic	+Alternative to petroleum fuel	–Not readily available, limited resource
Hydrogen	+Clean burning	–Difficult to store, poor lubricity

Figure 1: A fuels comparison derived from many sources. GF = gaseous fuel, LF = liquid fuel.

The following table has several key properties of interest of several fuels:

Fuel Name	Chemical Formula	Specific Gravity	AIT (deg. C)	a/f	Source
Methanol	C-H4-O (CH3-OH)	0.791	385	6.5	TA1
n-Octane	C8-H18	0.703	220	15.1	TA1
Diesel	C12-H26	0.85	210	15	TA1
BioDiesel	C12-H26	0.85	210	15	TA1
n-Heptane	C7-H16	0.684	215	15.2	TA1
Ethanol	C2-H6-O (CH5-OH)	0.789	365	9	TA1
BioEthanol	C2-H6-O (CH5-OH)	0.789	365	9	TA1
BioButanol		0.805	343	11.1	TA1
Butanol	C4-H10-O	0.805	343	11.1	TA1
JP8	n/a	0.8	240	15	TA1
Kerosene	C13-H28	0.8	210	15	TA4, TA7
Gasoline	C8-H18	0.75	280	15.1	TA7
Light Diesel	C8-H18	0.85	210	15	TA7
Medium Diesel	C14-H30	0.85	210	15	TA7
Heavy Diesel	C21-H44	0.85	210	15	TA7

Figure 2: The following values were extracted from [2].

II. Research Methodology

A. *Proposed work*

The research conducted during the reporting period of 1 Sept. 2007 and 31 August 2008 intended to complete the following tasks:

a. *Apex Seal Redesign for Durability* - New Design and New Material for COTS rotary engine (2 months) – sealing represents a significant weakness of the rotary engine. Leakage at the apex seals reduces compression ratio, thereby reducing the overall efficiency of the engine. Analysis and redesign of seals for improved wear, higher strength, reduced weight, and other improvements will be investigated.

b. *Fuel / Materials Compatibility Study* (1 Month) – Liquid hydrocarbon fuels are caustic for many plastics and polymers and therefore an investigation into which materials suffer in the presence of an array of fuels is needed.

c. *Endurance testing of existing engines for several fuels* (6 Months) – Engine mapping (power output vs. load and speed) will be carried out for three fuels on pre-existing engine platforms. This includes (a) standard glow fuel, (b) diesel fuel and (c) JP-8. Other fuels will be included in these studies if time permits.

i. ARO assistance to acquire JP-8 is specifically requested.

ii. Acquiring small quantities (1 to10 liters) of JP-8 at any one time has been problematic in the past for civilians.

d. *Engine diagnosis* (1 Month) – post endurance test strip down and evaluation.

e. *Liaison with complementary research tasks* (2 Months)

i. SiC TAPS (DARPA MTO) – Silicon carbide integration into the engine could support the use of novel sensors and actuators to improve performance.

ii. Electromagnetic Valve (ARL) – fuel metering—especially when performing fuel flexibility—may present an opportunity to improve the fuel flexible performance of the engine. However, this electromagnetic valve is in its nascent form and still needs development.

iii. O_2 Sensor (At risk funding) – oxygen sensors placed at the inlet and exhaust allow one to measure the stoichiometery of the combustion event. O_2 sensors being developed here in the Berkeley Micromechanical Analysis and Design lab are working on oxygen sensors that can be integrated into the combustion chamber; thereby improving the information of the combustion event itself.

Given the importance of the investigation into the fuel flexibility performance of these engines, the endurance testing was prioritized and other tasks were completed as time permitted. The first real step was to determine how to perform engine mapping: measuring power output, load, and speed for a given set of input variables: throttle, air-to-fuel ratio, temperature, fuel, etc.

B. *Development of Small-Scale Engine Dynamometer*

Historically, measuring the power output and other dyno-like-parameters for these small engines proved difficult due to the lack of professional test equipment available on this scale. Larger engine dynamometers for transportation-size vehicles are readily available however represent a significant cost (in the range of $10-100k). Unable to find a dynamometer that could allow for long endurance testing (power dissipation system with long-term heat dissipation capabilities), a dynamometer system was designed and built in house.

Figure 3 shows the first iteration design for the small-scale engine dynamometer. This design sought to resolve the legacy of problems with former dynamometers that were built in-house to obtain power data. Specifically, poor shaft alignment caused couplings to break constantly during test.

Residual fuel further degraded the fastening features of the old setup. Lastly, the dissipation systems (i.e. the mini Maxon motors) would burn up due to overloading and represented a large cost (each motor ~$400 each).

Using a host of off the shelf components in addition to low-cost anodized aluminum blocks, the fuel flexible engine was designed to mount the system with its drive shaft precisely aligned with the three-phase AC motor. This motor—which provides the power generation and starter motor—is mounted in a cradle that is free to rotate in two, concentric ball bearings. This “cradle” enables the measurement of mechanical torque.

The electric starter motor is controlled using a specialized servo circuit that sends appropriate signals to an electronic speed controller (ESC) for the generator motor. Both the motor and the ESC were manufactured by Kontronik—a hobby motor manufacturer specializing in precision, high power electric motors.

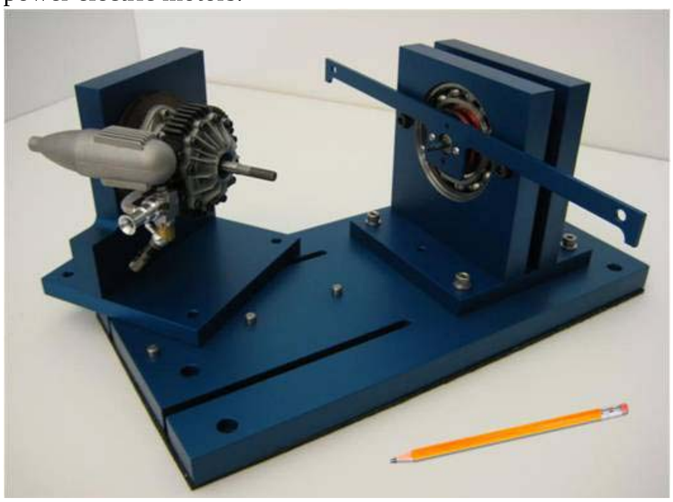

Figure 3: Original cradle dynamometer to test power output of fuel-flexible rotary engine.

Figure 4: Resistor bank to adjust physical load on engine.

The remaining mechanical parts (blue) were designed using 3D CAD tools in-house and manufacturing was outsourced to a local vendor. The functional requirements for this system were: precision alignment, quick lead time, inexpensive, mechanically and chemically robust, easy to assemble and disassemble, and incorporating as few custom parts as possible.

The functional requirements were met, however some rework was needed to allow for quicker disassembly and to address new needs (i.e. servo control of air-to-fuel ratio).

Figure 3 only shows the electro-mechanical portions of this system; the load and complementary systems still needed design and manufacture such as the loading system and the control system.

The dissipation system comprised of an industrial size heat sink, quantity eighteen, fifteen-ohm resistors in parallel to load the electrical generator thereby loading the engine is shown in Figure 4. The challenge for this situation is achieving an extremely low resistance and sourcing resistors that can handle the heat dissipation. The better the load matches the internal resistance of the electrical windings, the larger torque that can be applied to the engine. This load is connected to the three-phase AC motor using an AC/DC converter.

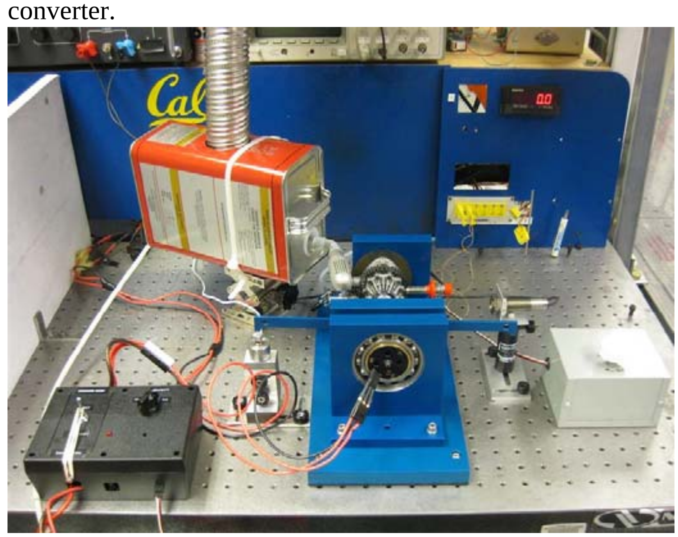

Figure 5: Fuel-flexible engine test setup.

The dissipation circuit is not shown in Figure 4 but is connected to the electric motor via the black box switching unit and motor speed control in the lower left-hand corner. Additionally, the waste alcohol can was used as a temporary reservoir for the exhaust and the small gray box on the right-hand side is the throttle servo control box.

The dynamometer proceeded to work as designed and data was collected. However, some problems surfaced with this particular design in that the ESCs would “burn up” from the unreliable switching from “start mode” to “generate mode.”In the start mode, an active 14V and up to 20A are presented at the input terminals to the speed controller. If the engine turns over, it begins to generate a back EMF on the electric motor, driving electrons back into the ESC. This caused premature

failure of the starting controller and thus we gravitated towards a mechanical starting solution.

Additionally, communication issues with the data acquisition software and the mass fuel flow rate scale (Ohaus 20000g scale) stalled the system on several occasions.

The data acquisition was achieved using the National Instruments multi-channel DAQ card along with the LabVIEW 8.5 software. A dashboard with the needed tools and plots was designed specifically for this dynamometer system (Figure 6).

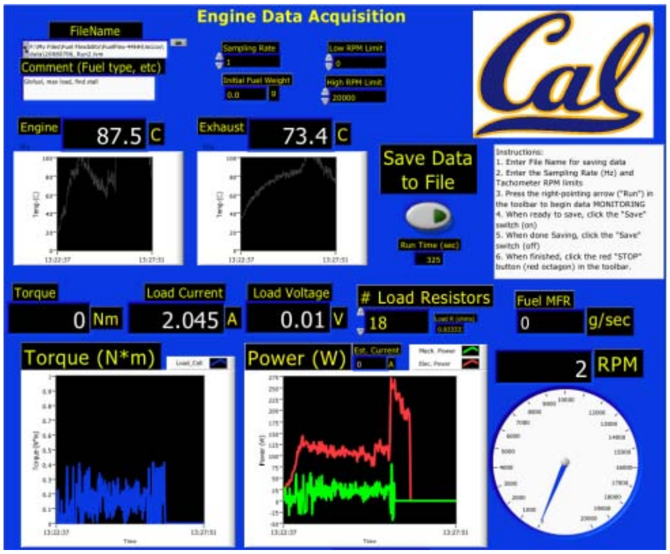

Figure 6: Fuel-flexible engine dynamometer dashboard from LabVIEW VI.

III. Results

Using the newly designed test setup data was collected for three fuels: methanol, 87 octane (auto grade), and Jet Propulsion 8 (aka JP8). Blends of fuels were tested however no significant data sets were produced due to the imperfect characterization of the fuel compositions.

Several plots were generated however for the power produced for each of the three primary fuels listed above. The first plot is one showing the average powers at a given speed for the three fuels.

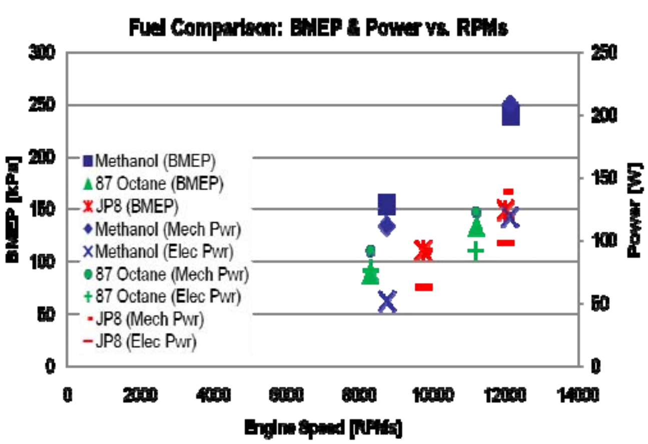

Figure 7: Plot of demonstrated fuel flexibility of three fuels.

For reference, the BMEP for a Honda Civic type R is 1190kPa.

The above plot lists mechanical power, electrical power and brake mean effective pressure (BMEP). The mechanical power and BMEP are of primary importance as the electrical power does not specifically measure the output of the engine like that of the mechanical power. The BMEP is proportional to the mechanical power but normalizes this power based on displacement.

The following plots show the power versus engine speed for each fuel tested at various throttle positions.

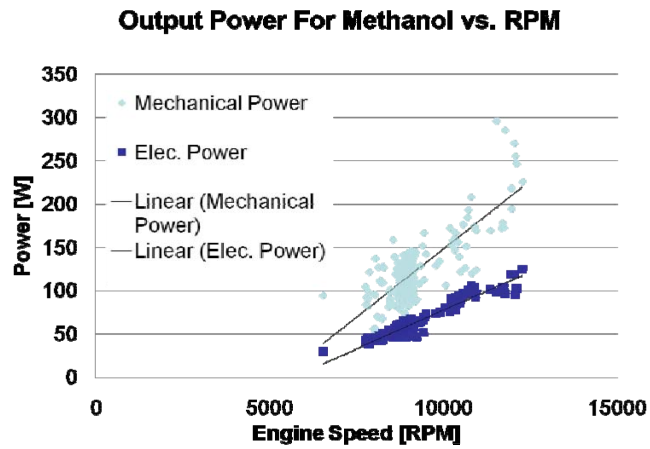

Figure 8: Power curve for engine combusting Methanol + Nitromethane

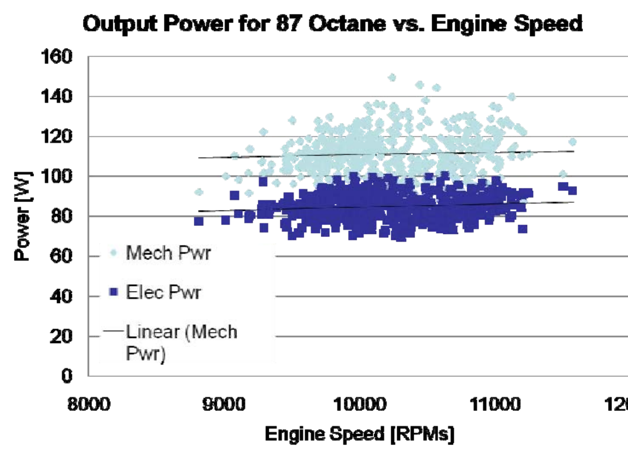

Figure 9: Power curve for engine combusting 87 octane, transport-grade fuel.

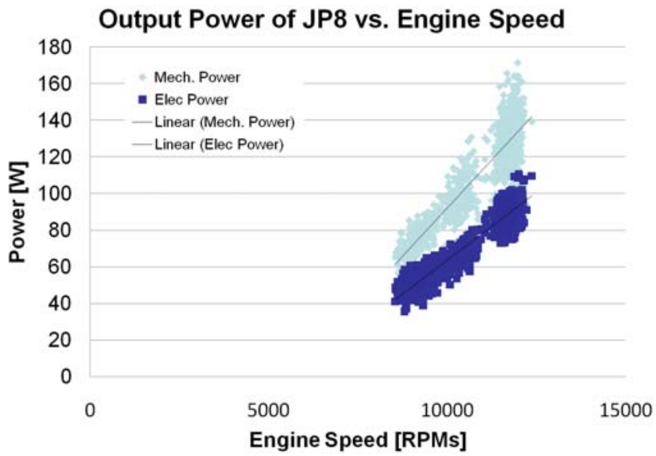

Figure 10: Power curve for engine combusting JP8.

Strong conclusions are difficult to make when the throttle position varies widely amongst each fuel. However, the difficulty in simply maintaining proper combustion of the engine prevented the easy variance and measurement of this property. Future versions of this setup will incorporate computer control and measurement to facilitate stronger conclusions about the engine performance and dependencies on the key variables.

IV. DISCUSSION

A. *The Small-Scale Rotary Engine is Fuel Flexible*

The fact that the engine produced power on more than one suggests that this engine is fuel flexible. Although the engine needed a lot of attention when operating other fuels, this achievement yields hope that sensing technologies and automatic controls could effectively manage the performance of the engine under multi-fuel operation.

Specifically, the parameters that needed constant attention (i.e. measurement) and adjustment were the external housing temperature, throttle, glow plug intensity and air-to-fuel ratio (or fuel flow needle valve).

The experiments where methanol was used were particularly successful as this is the fuel for which the engine was originally designed. Methanol was used as a starter fuel for the other non-standard fuels tested.

The experiment with gasoline proved to be more problematic as the properties of octane are quite different from methanol; namely the air-to-fuel ratios. Thus, during sustained combustion, the throttle position seemed to have little effect on the power output but the engine preferred throttle positions closer to wide-open-throttle (WOT). The engine also needed to have the glow plug element “on” supplying additional power and heat to the combustion event.

For JP8, the operation was also less stable; however appeared to run better than the Octane. Having more throttle response, the JP8 ran for at least 7-8 minutes uninterrupted and produced a modest amount of power compared to the other fuels.

B. *External Engine Temperature*

The varying auto ignition temperatures of the fuels combusted required that the engine be operated at different temperatures (see Figure 2). While the exhaust temperature and engine housing temperature were being measured, the temperature of the engine was not well controlled. The cooling fans were either placed directly on the engine, slightly off axis, or removed from cooling all together. JP8 for example, had better performance under hotter engine temperatures.

Therefore, installation of a better cooling management system would widen the fuel-flexible range of the engine. The next iteration on the cooling system would be to simply integrate an electronic fan speed adjust that could be controlled and measured by computer.

C. *Accurate Throttle Control*

While the adjustment of the throttle was consistent, reliable, and real-time, the measured position of the throttle was measured in these experiments, by eye (or feel). Getting the engine to turn over required frequent adjustment of the throttle and only when the engine appeared slightly stable was the throttle position “set” by eye and data recorded. This is why the data sets call out a power at a given engine speed and an approximate throttle position.

Therefore, efforts are being made to use an Arduino microcontroller to control the throttle and the output throttle signal being measured by LabVIEW.

D. *Glow Plug Intensity*

Actively powering the glow plug was an important engine parameter for fuels other than the methanol + nitromethane mixture. The higher activation energy of the other fuels in addition to the low air-to-fuel ratio required by methanol suggests that more heat was needed to propagate combustion. The recorded glow plug intensity was only adjusted in binary to an “on” or “off” position however the researchers believe that accurate and dynamic control of this heating element will be necessary to reliably control the fuel-flexible performance of the engine.

E. *Power Production*

As can be seen from Figure 7 to Figure 10, the engine generated a range of output mechanical power for three different fuels. Currently no system has been developed to store this power but such systems likely exist commercially. A Honda 2000i generator was obtained and investigations of its power management systems will be conducted. High capacity lithium polymer batteries and flow batteries exist that can take rapid charges and have high storage capacity. This will also be investigated.

F. *Liaison with Complementary Research at Berkeley*

BMAD has several students working on high-temperature, high-pressure, harsh environment sensors for engine-type applications. Novel O_2 sensor developments using new materials and their fit into this small engine were explored, but

reasoned that the technology is too immature at this point to be helpful. This was also true for the electromagnetic fuel flow valve.

However, one BMAD researcher has designed and built a Si-based temperature sensor and through collaboration, the two groups have made an engine and sensor ready for survivability testing inside an engine. However, the risk of catastrophic failure of the engine was too great given the project's funding outlook and has been put on a temporary hold. Should more funding be awarded to this project, this experiment is ready to be conducted (Figure 11).

Figure 11: SiC temperature sensor embedded into near Top-Dead-Center position to control Carb-Smart.

G. *Electronic Control for Enhanced Fuel Flexibility*

The endurance testing consumed a significant portion of the research effort; however designs and decisions were made with the expectation that electronic control would be integrated. The Arduino microcontroller has been identified as a low cost, rapid development tool that can handle the real-time needs of this system.

Additionally, one commercially available system, the "Smart Carb" was purchased and will be installed. This device measures the external housing temperature and dynamically adjusts the air-to-fuel ratio of the engine to keep a near-constant engine temperature. This would have proved useful when the first engine catastrophically overheated.

Figure 12: "Carb-smart" active fuel-to-air ratio controller for improved performance. First step to active control of engine and fuel flexiblity.

The latest modifications to the setup include a rigid-in-torsion flexible shaft in order to drive the changes in the air-to-fuel ratio.

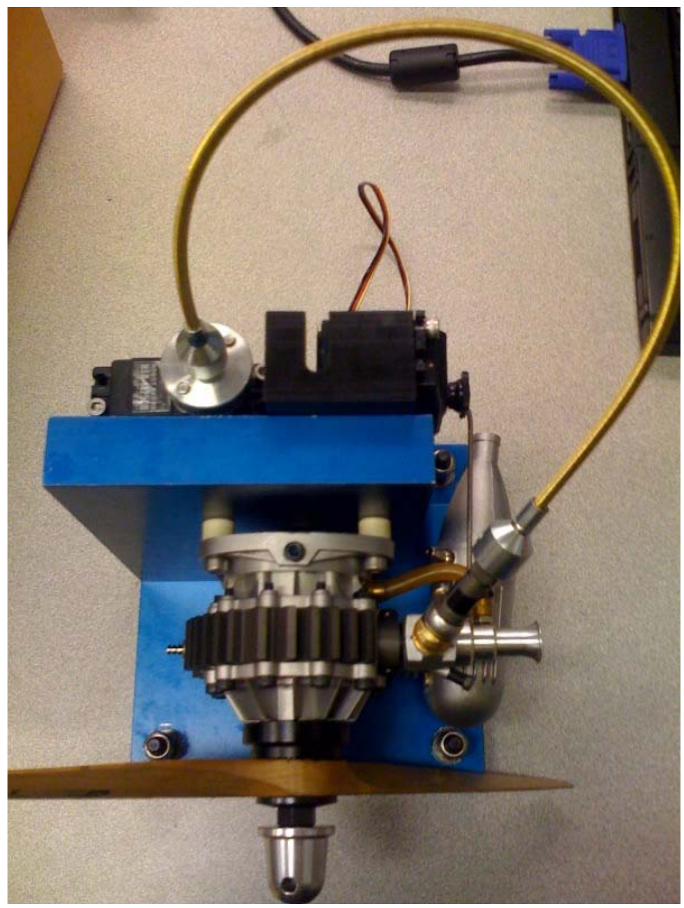

Figure 13: torsional flex shaft integrated onto the small scale rotary engine. Will first be controlled by the "Smart Carb" then using the Arduino microcontroller, custom algorithms will be developed to better address the fuel-flexible performance requirements.

V. Conclusions

The conclusions for this research are:

- This 4.97cc Wankel Rotary engine is in fact fuel flexible
- Glow plug intensity, external engine temperature, and air-to-fuel ratio control will be key to enable robust fuel flexibility
- Active computer control of such parameters will be necessary to sustain fuel-flexible operation during fuel transitions
- The dynamometer while functional, needs serious improvement to its mass fuel flow rate measurements, starting strategy, and loading capability
- A pre-combustion, in-situ combustion, and post combustion strategy is needed to make reliable fuel-flexible operation possible

Appendix

A. *Standard Operating Procedures (SOP)*

A standard operating procedure and protocol were defined to better ensure the repeatability of the results. That procedure was as follows:

1. SAFETY FIRST! Safety Glasses and ear protection for everyone in the room.
2. Ensure that all bolts / screws are tightened to their proper torque.
3. Start LabVIEW, ensure all sensors / actuators are powered up and ready to transmit data to computer (note dedicated power strip):
   i. Turn on NI DAQ block (switch at back near power cord).
   ii. Plug in load cell.
   iii. Plug in tachometer.
   iv. Connect dissipation voltage cable. Verify presence of attenuator and / or the large voltage divider.
   v. Set the max, min on the RPM meter.
   vi. Set your sample rate to somewhere between 1-10 samples / second. Six+ measurements were taken and efforts were taken to prevent the overloading of the system resources.
   vii. Clear all charts (right-click: Data Operations -> Clear Data).
   viii. Enter the fuel type, etc in the comments field.
4. Power up fuel scale.
5. Check the proper placement of thermocouples (the exhaust thermocouple can shift during operation / break-down).
6. Start cooling and exhaust fans.
   i. Start cooling fans (squirrel cage + overhead AirKing fans.
   ii. Start cooling fans on dissipation heat sink (by turning on power strip).
   iii. Start exhaust suction pump / fan (at the wall over by the whiteboard).
7. Set voltage on Tenma power supply (12V) to adequately power glow plug (for start-up) and connect to Hobbico Power Panel.
8. Find the lab timer, and fill fuel tank. Be aware of what is on the scale when you start. It is only precise to 0.1 grams (and it has some error). Also, be aware that the fans put a downward force on the scale so average your measurements.
9. Position both thermocouples: one in the exhaust, one on the engine housing near top dead center
10. Power up the high current power supply (20A, 14V) starter motor.
11. Securely fasten the flexible coupling from the electric motor to the engine.

Engine Running

1. FLIP THE SWITCH ON THE STARTER CIRCUIT FROM START TO DISSIPATE.
2. Check to make sure the RPM IR light is positioned correctly as it may need realignment after each setup / break-down.

Generating Engine Power Plots

As described in *Land and Sea's* dynamometer talk tech notes [1].

1. Warm up engine.
2. Open throttle to full load.
3. Regulate the RPM using the "absorber brake." This is our dissipation circuit.
4. Slowly step through RPMs by relieving the absorber brake.
5. Finish collecting data, back off throttle.

B. *Research project scope and achievements*

Accomplishments for Reporting Period

Bullet point summary:

- Designed and built a robust engine safety cage to enclose the engine test stand and provide cooling fan mount
- Designed and built a small-scale engine dynamometer consisting of:
  - The main engine and electric motor mounts (Figure 3, blue components)
  - The dynamometer measurement software code using LabVIEW
  - The resistive load circuit
- Further testing and re-evaluation of BMEP values for each fuel:
  - o Methanol: BMEP 240kPa at 12000 RPMs (~50% WOT)
  - o 87 Octane: BMEP 89kPa at 8300 RPMs (~90% WOT)
  - o JP8: BMEP 149kPa at 12000 RPMs (~60% WOT)
- Post-testing evaluation and debugging of engines
  - Engines that operated at elevated temperatures appear to now have reliability issues during start up
  - A new engine has been purchased to debug each of the older engines, component by component

- Refined experimental setup to accommodate better engine break-in procedures and reliable operation
- Re-located experimental setup into a high-flow fume hood for significantly improved safety
- Installed a non-functional temperature sensor into the side plate of the engine in order to test the survivability of SiC sensors in small-scale rotary engines (Figure 11). Testing will commence once engines, A and B, are operational.
- Determined that excessive temperatures required for combustion of JP8 are harmful to long-term engine operation.
- Obtained a temperature-controlled fuel-to-air ratio adjusting system (Carb-Smart) to maintain proper combustion stoichiometry (Figure 12)

September 2007 – March 2008

Identification of the new test setup needs were determined. The main deficiencies of the old setup were safety, robustness, and measurement ability. Safety measures to protect researchers from engine hazards (carcinogenic exhaust gases, high-speed moving parts, high temperatures) were designed and implemented. To ensure accurate torque and power measurements, the new design addressed limitations in power dissipation, throttle control, shaft misalignments, exhaust management, and data acquisition. Power dissipation was addressed by using a large cooling fan (air flow to above 3600CFM). The new design was created with the intent to be precision machined and be more assembly friendly.

March 2008 – September 2008

The commercially available off the shelf (COTS), 4.97cc O.S. Graupner rotary engine, was determined to be fuel flexible. Without any modifications, this engine generated power from three fuels—glowfuel, gasoline, and JP8—and produced Brake Mean Effective Pressures (BMEPs) of 240kPa, 89kPa, and 149kPa, respectively (Figure 6). The small-scale engine dynamometer was built to measure the output electrical and mechanical power, mechanical torque, engine and exhaust temperatures, and fuel mass flow rate.

September 2008 – March 2009

Engine testing system with 7+ sensors and actuators was performed but not without debugging challenges. Active throttle control was enabled and can be adjusted based on engine metrics. An average mass flow rate was measured for the engine at 0.19g/s and from that metric, the thermal efficiency was calculated to be ~6.6 percent.

March 2009 – May 2009

After engines were tested using multiple fuels, problems developed with their functionality. Each suspect engine component was inspected, cleaned, rebuilt, and re-tested. Neither engine currently works. A new engine was obtained, and gone through a specified "run-in" period to produce output power. The new engine is being used to further debug the other damaged engines in order to determine the failure mechanisms. Some preliminary analysis on Apex seal forces has also been conducted to aid the design of new sealing mechanisms. Lastly, a silicon-based temperature sensor fabricated by S. Wodin-Schwartz was embedded into the side wear plate of our engine. The survivability of this chip will be evaluated in future tests.

Collaborations and Technology Transfer

- Previous rotary engine research funded by DARPA has generated a considerable foundation of knowledge, resources, and tools to quickly jumpstart this specific project.
- The results of this research will also strengthen the technical rationale for future MURI BAA submissions.
- Collaboration with former researchers and staff scientists within the energy sector (biofuels) is initiated.
- Other research within the Berkeley Sensor and Actuator Center (BSAC) will be readily leveraged when integrating sensor technology into the engine.

Resulting Journal Publications During Reporting Period

- N/A

Intellectual Property and Invention Disclosures

- N/A

Graduate Students Involved During Reporting Period

- Chris McCoy – is a 3rd year graduate student pursuing his Ph.D. in design with emphasis in MEMS. Chris holds a B.S. in Mechanical Engineering from UC Berkeley (2005) and has both research and industry experience. Chris worked on developing a MEMS-based carburetion system, an engine balance/counterweight system, and characterizing the pressure within the UC Berkeley 1500mm3 rotary engine. In 2006, he worked at FormFactor Inc. designing and developing products for the market leader in wafer test products.

- John Réville – GRADUATED MAY 2009 - A 2nd year graduate student that currently holds his MS in mechanical engineering from the Ecole Centrale de Lille. Through his education, he has developed a vast knowledge of thermodynamics and fluid dynamics and plans to pursue his Ph.D.

- Jesse Limtiaco – GRADUATED DECEMBER 2008 - 2nd year graduate student pursuing a Ph.D. in Combustion and Thermal Sciences. Graduated from UC Berkeley with a degree in Engineering Physics May 2007. Has combustion research experience as an undergrad with Professor Carlos Fernandez-Pello as well as experience programming in National Instruments LabVIEW for data acquisition purposes.

Awards, Honors and Appointments

Poster Presentation at Meeting:

McCoy, C., Réville, J. “Fuel flexible engine design for optimal combustion.” Poster Session. Massachusetts Institute of Technology Energy Conference. March 2009.

McCoy, C. “Fuel flexible engine design for optimal combustion.” presented at BSAC Spring 2008 IAB Meeting, Mar. 2009.

McCoy, C. “Fuel flexible engine design for optimal combustion.” presented at BSAC Fall 2008 IAB Meeting, Sept. 2008.

McCoy, C. “Fuel flexible engine design for optimal combustion.” presented at BSAC Spring 2009 IAB Meeting, Mar. 2008.

McCoy, C. “Fuel flexible engine design for optimal combustion.” presented at BSAC Fall 2009 IAB Meeting, Sept. 2007.

Masters Degrees

Limtiaco, J. “Data acquisition for small-scale fuel flexible rotary engines.” Master's Thesis, Internal UC Document, Dept. of Mechanical Engineering, May. 2009.

Reville, J., “The Wankel engine and fuel flexibility: a performance review.” Master’s Thesis. Dept. of Mechanical Engineering, UC Berkeley. May 2009..

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References

[1] “Dyno Tech Talk: about Dynamometers and Testing.” Land and Sea’s tech notes. Accessed on 3 May 2008. http://www.land-and-sea.com/dyno-tech-talk/dyno-tech-talk.htm

[2] Borman, Ragland, Combustion Engineering, Tables 1-7

[3] Kontronik Motors USA. Accessed on 29 January 2010 http://www.kontronikusa.com/

[4] “Commanders in Iraq Urgently Request Renewable Power Options,” Defense Industry Daily. 27-Jun-2007. Accessed on: 29 January 2010. http://www.defenseindustrydaily.com/commanders-in-iraq-urgently-request-renewable-power-options-02548/